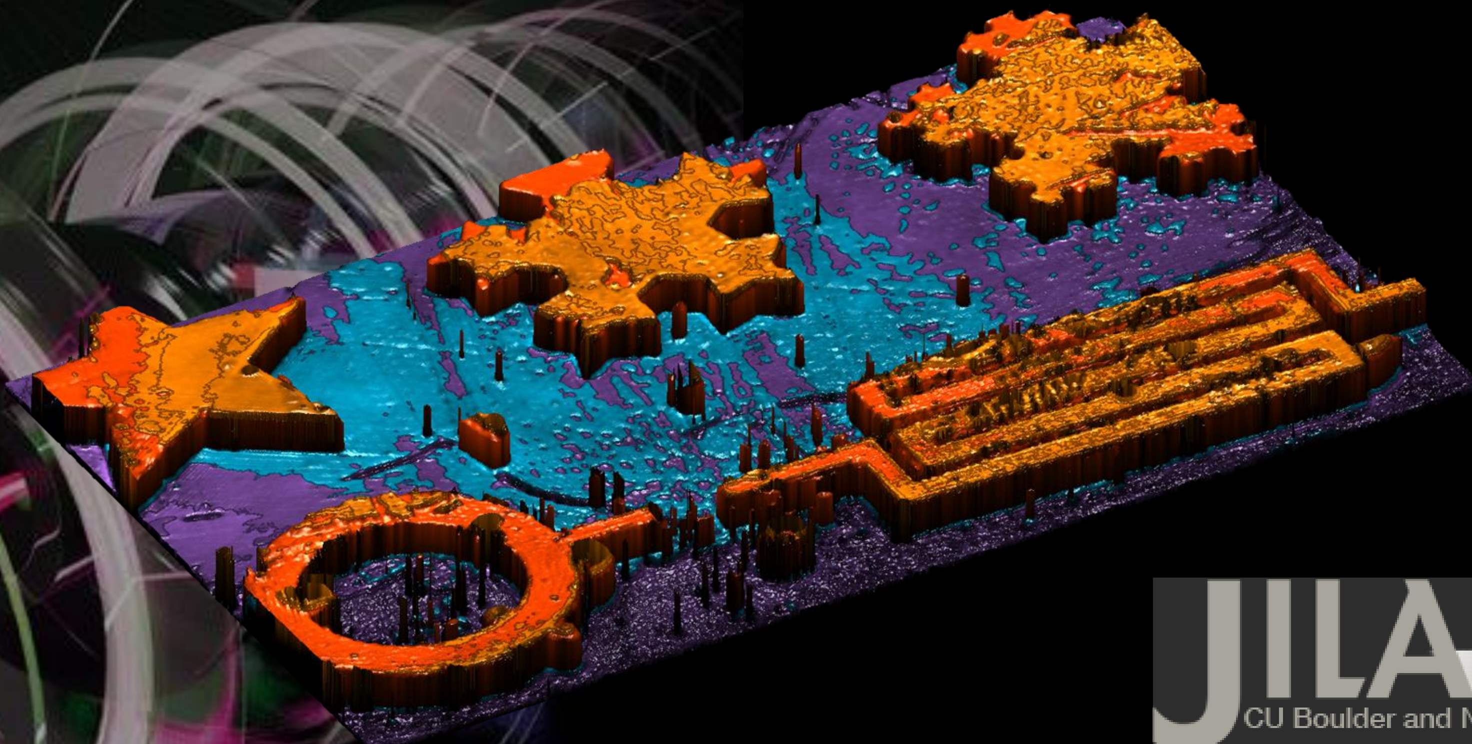
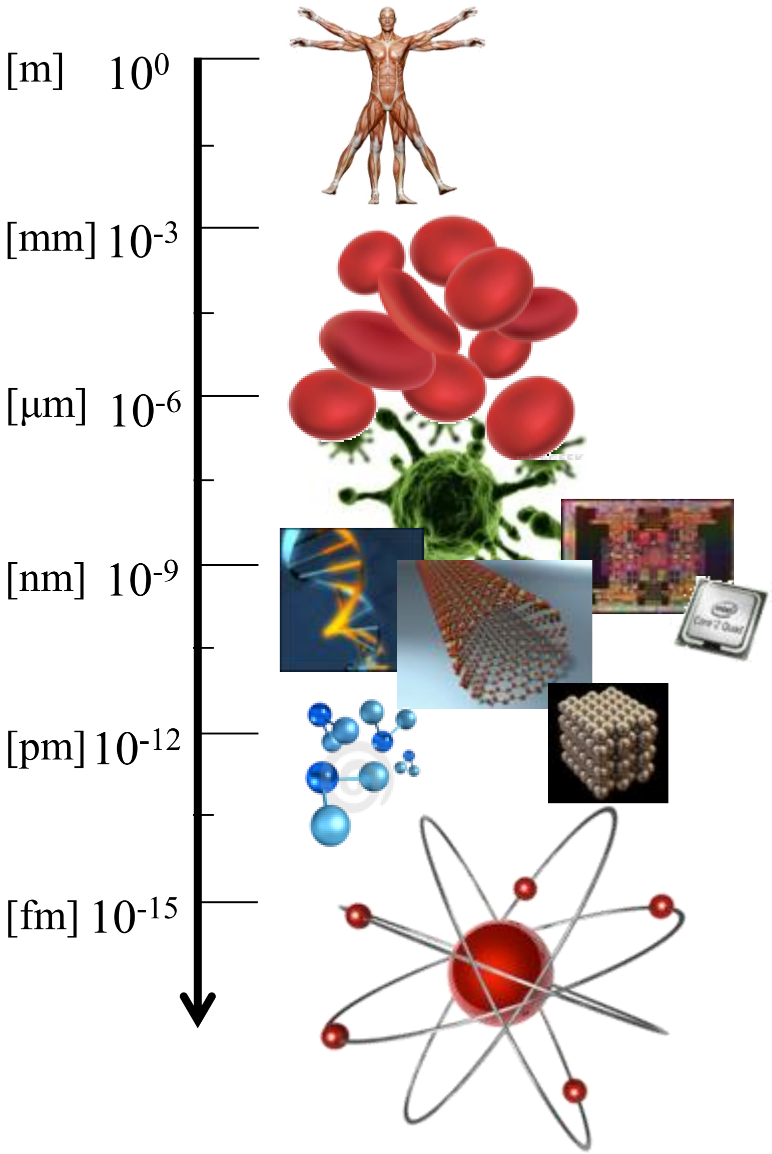
Tabletop-Scale EUV Coherent Phase-And-Amplitude Imaging Using High Harmonics



JILA
CU Boulder and NIST

Daniel Adams

Coherent EUV Nano-probe



Human

Blood Cell

Virus

Transistor Nanotubes

DNA

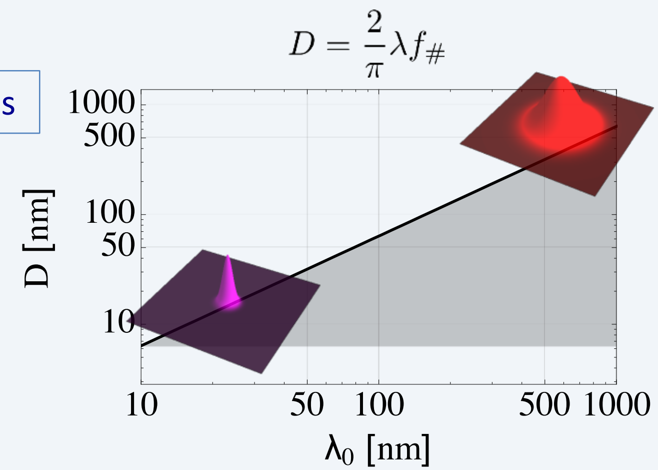
Molecular Atomic Spacing

Nuclear Diameter

Uncertainty Principle

(Gaussian, **e**$^{-2}$ Intensity)

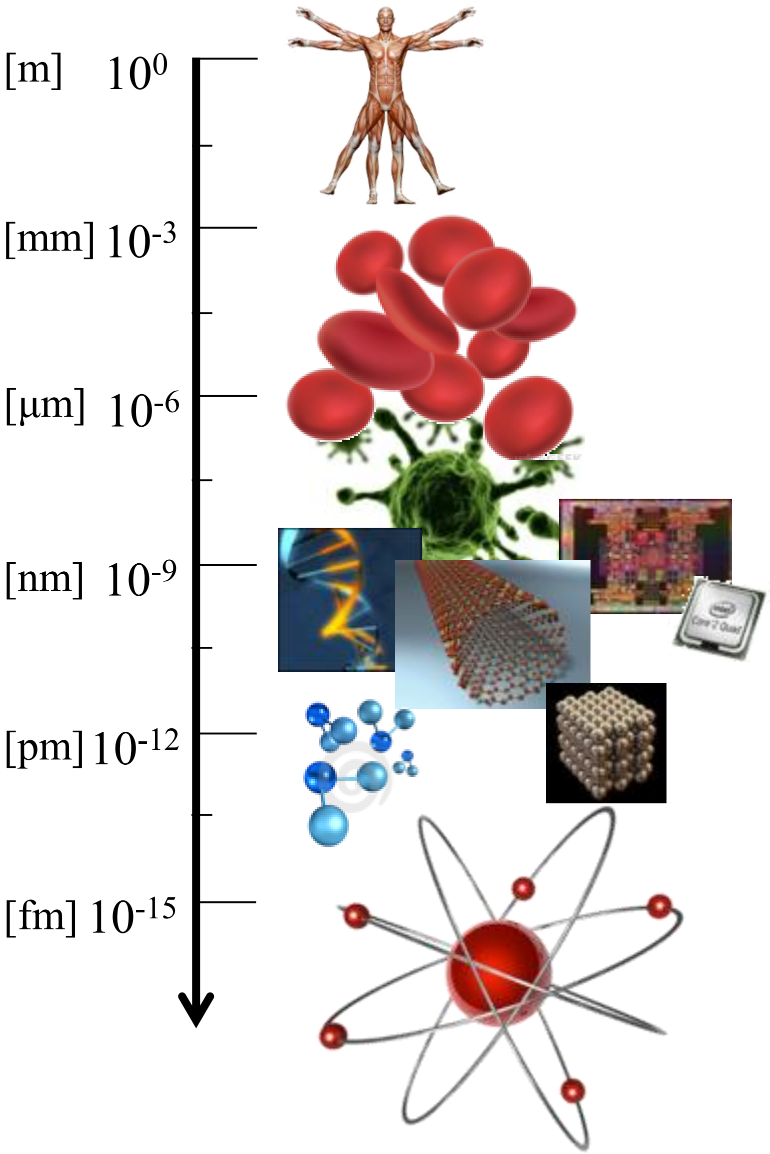
$\otimes x \otimes \kappa \sim 1.2$



Coherent X-rays are ideal probes of the nanoworld:

- Penetrate thick objects
- Elemental and chemical specificity
- Image small features in 3D at wavelength limit
- Capture all dynamics relevant to function

Coherent EUV Nano-probe



Human

Blood Cell

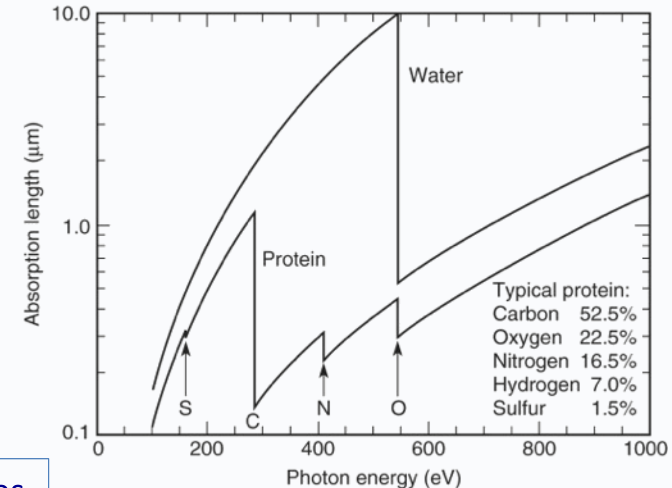
Virus

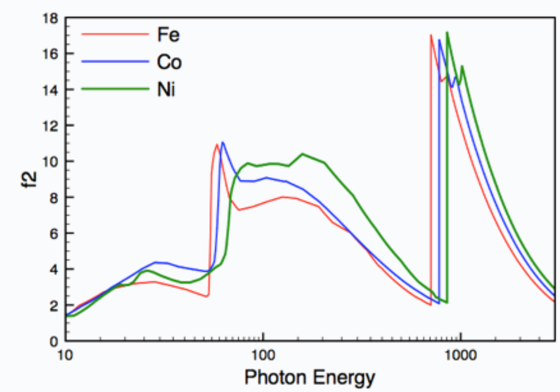
Transistor Nanotubes

DNA

Molecular Atomic Spacing

Nuclear Diameter





Coherent X-rays are ideal probes of the nanoworld:

- Penetrate thick objects
- Elemental and chemical specificity
- Image small features in 3D at wavelength limit
- Capture all dynamics relevant to function

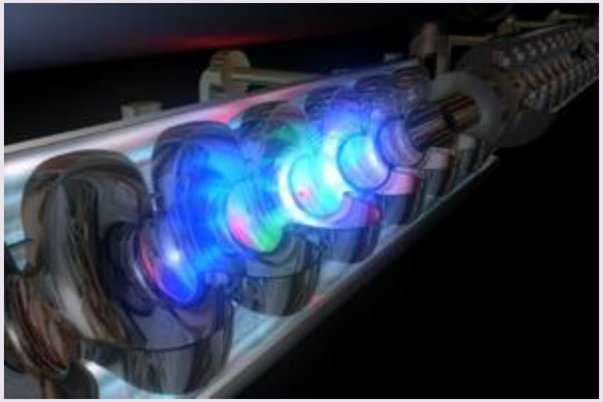
Coherent EUV Sources

FACILITY SCALE SOURCES

Synchrotron

Miao et al., *Nature*, **400**, 342 (1999)

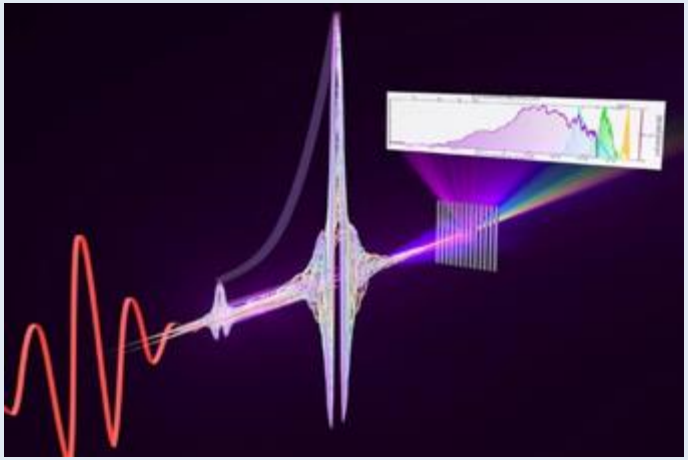
Free Electron Laser



Chapman et al., *Nature Phys.* **2**, 839 (2006)

TABLETOP SOURCES

High harmonics



T. Popmintchev et. al., *Science*, **336**, 6086, (2012)

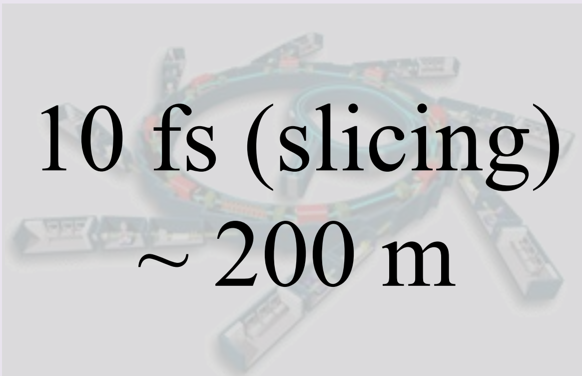
EUV laser source at 13nm

Martz et al, *Optics Letters,* **35**, 1632 (2010)

Coherent EUV Sources

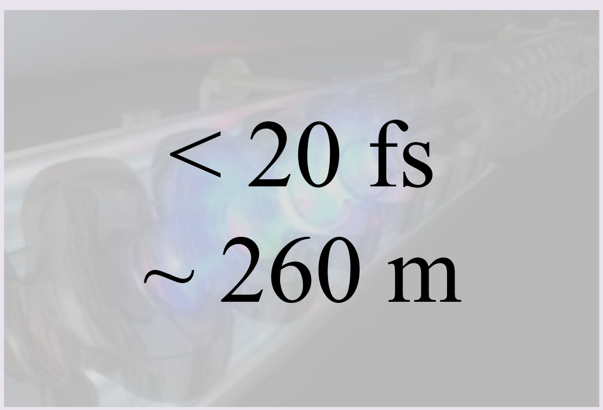
FACILITY SCALE SOURCES

Synchrotron



Miao et al., *Nature*, **400**, 342 (1999)

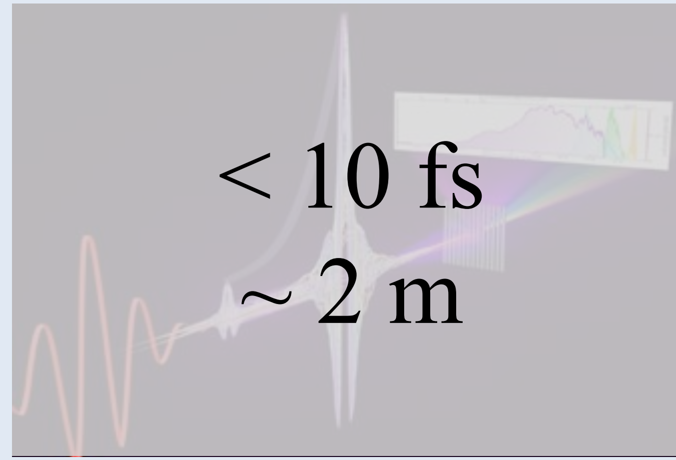
Free Electron Laser



Chapman et al., *Nature Phys.* **2**, 839 (2006)

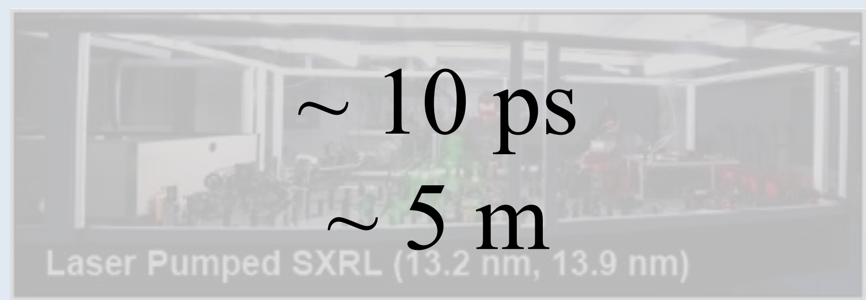
TABLETOP SOURCES

High harmonics



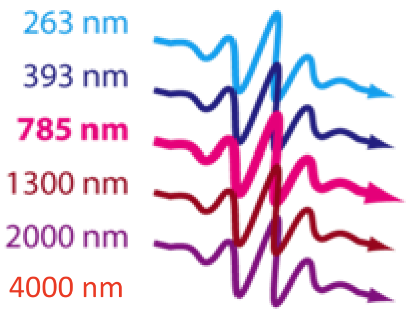
T. Popmintchev et. al., *Science*, **336**, 6086, (2012)

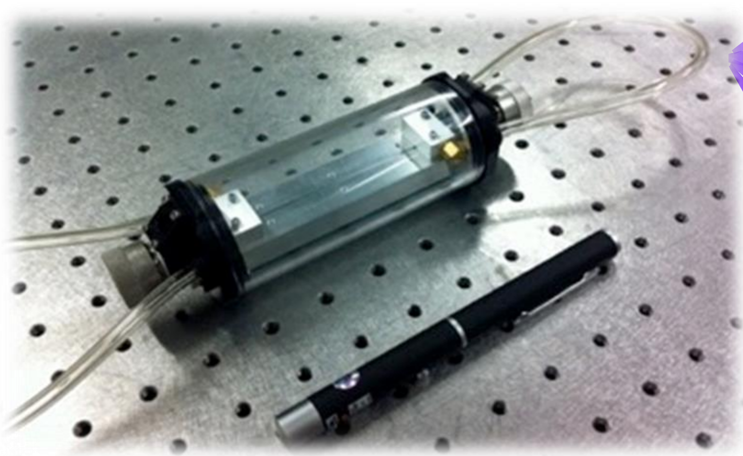
EUV laser source at 13nm

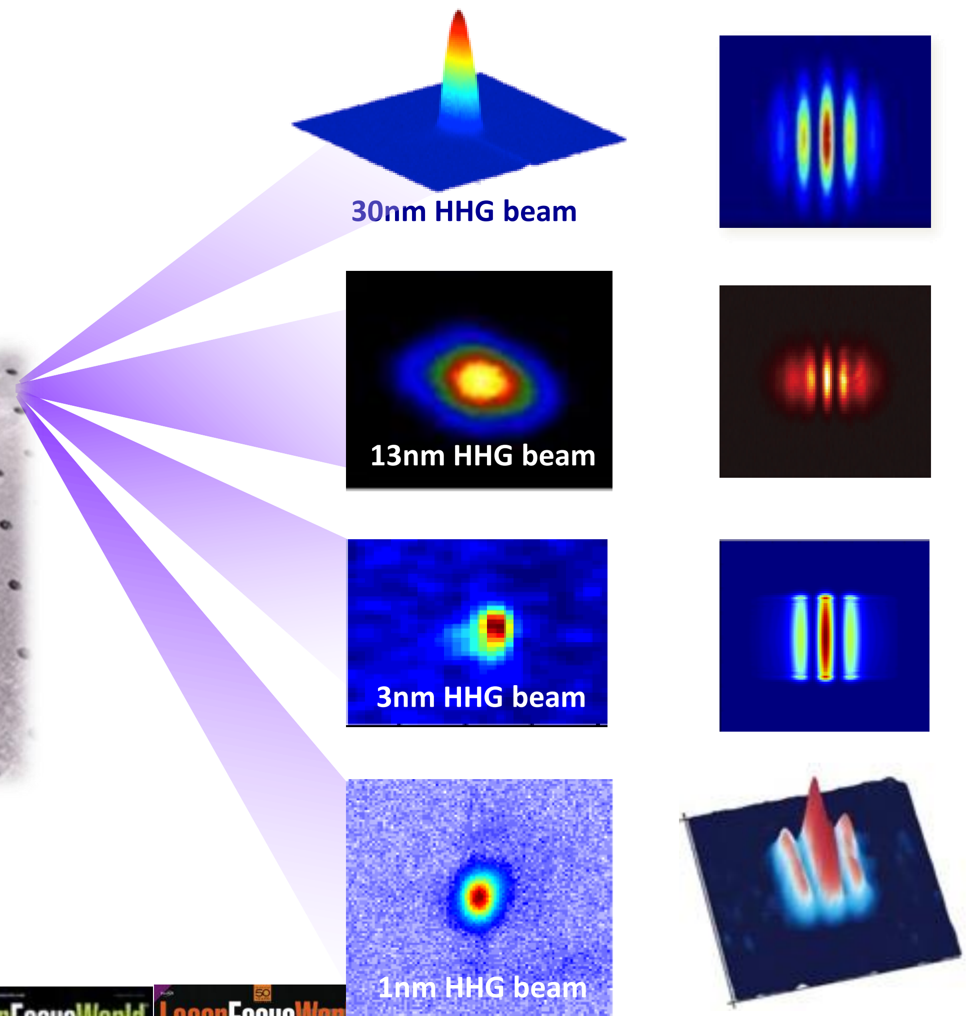


Martz et al, *Optics Letters*, **35**, 1632 (2010)

Bright Coherent Beams From UV To keV





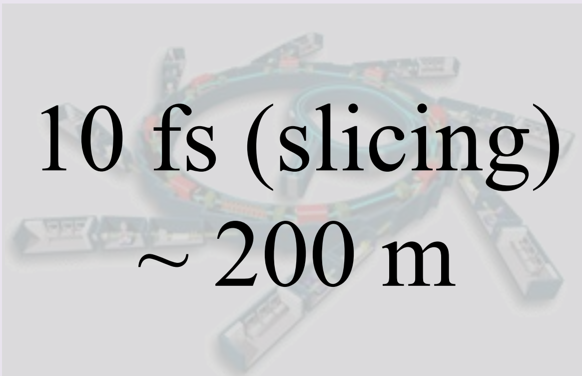


Science ***280***, *1412 (1998)*
Science ***297***, *376 (2002)*
Science ***336***, *1287 (2012)*
Pat. No. 8,462,824 (2013)

Coherent EUV Sources

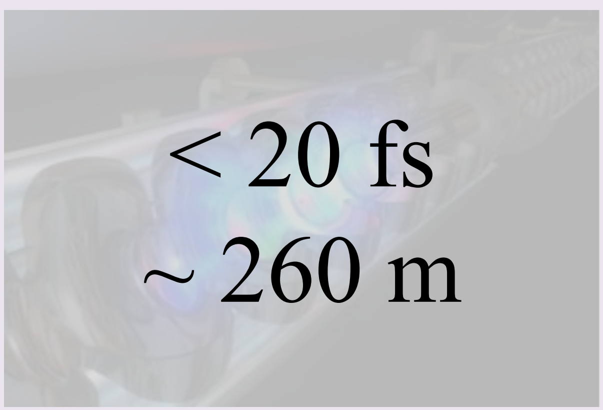
FACILITY SCALE SOURCES

Synchrotron



Miao et al., *Nature*, **400**, 342 (1999)

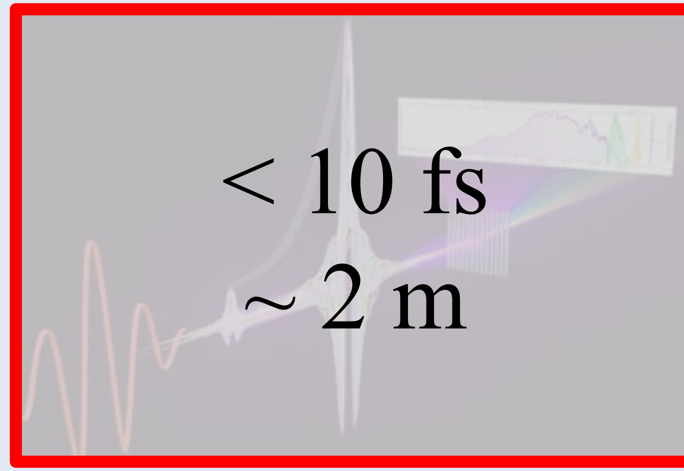
Free Electron Laser



Chapman et al., *Nature Phys.* **2**, 839 (2006)

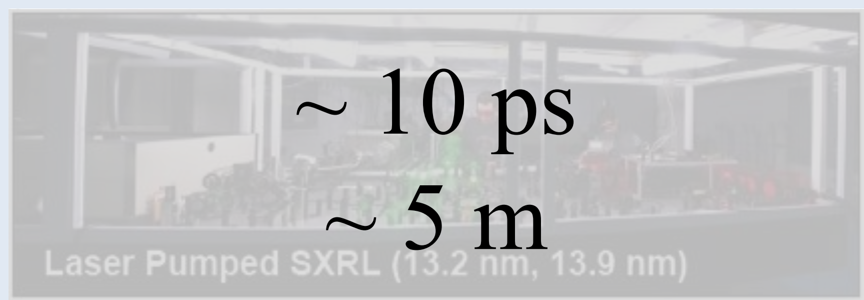
TABLETOP SOURCES

High harmonics



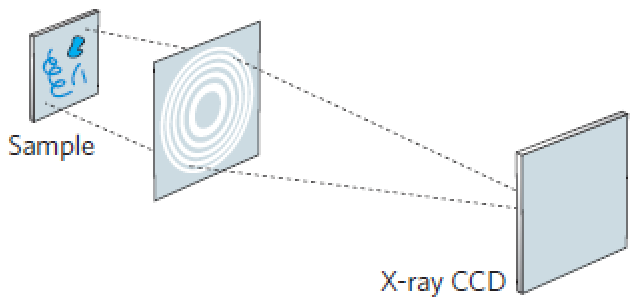
T. Popmintchev et. al., *Science*, **336**, 6086, (2012)

EUV laser source at 13nm

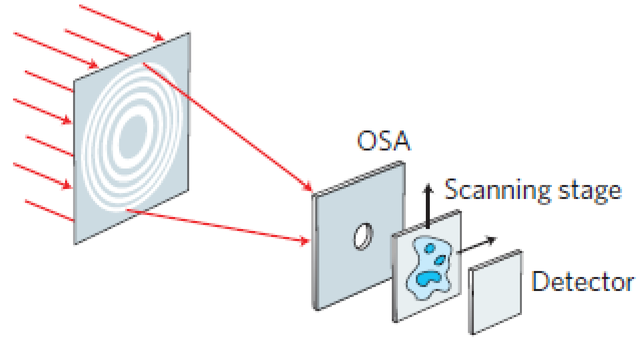


Martz et al, *Optics Letters*, **35**, 1632 (2010)

EUV and X-ray Microscopy Techniques



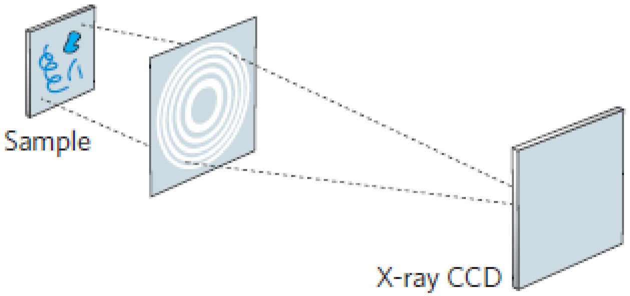
Full-field Zone Plate Microscopy



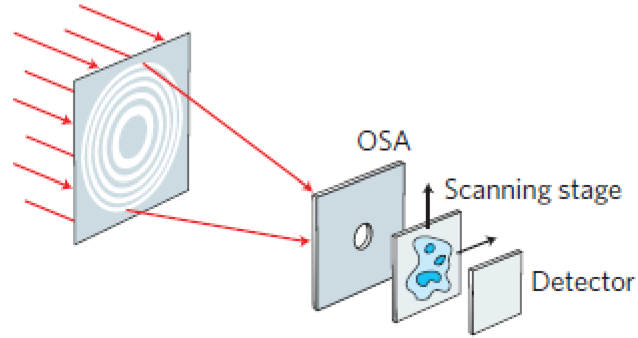
Scanning Transmission X-ray Microscopy

Sakdinawat and Attwood, *Nature Photonics*, **4**, 840 (2010)

EUV and X-ray Microscopy Techniques



Full-field Zone Plate Microscopy



Scanning Transmission X-ray Microscopy

Sakdinawat and Attwood, *Nature Photonics*, **4**, 840 (2010)

Acta Cryst. (1952). **5**, 843

Some implications of a theorem due to Shannon. By D. Sayre, *Johnson Foundation for Medical Physics, University of Pennsylvania, Philadelphia 4, Pennsylvania, U. S. A.*

(*Received* 3 *July* 1952)

Shannon (1949), in the field of communication theory, has given the following theorem: If a function $d(x)$ is known to vanish outside the points $x = \pm a/2$, then its Fourier transform $F(X)$ is completely specified by the values which it assumes at the points $X = 0, \pm 1/a, \pm 2/a, \ldots$. In fact, the continuous $F(X)$ may be filled in merely by laying down the function $\sin \pi a X / \pi a X$ at each of the above points, with weight equal to the value of $F(X)$ at that point, and adding.

Now the electron-density function $d(x)$ describing a single unit cell of a crystal vanishes outside the points $x = \pm a/2$, where a is the length of the cell. The reciprocal-lattice points are at $X = 0, \pm 1/a, \pm 2/a, \ldots$, and hence the experimentally observable values of $F(X)$ would suffice, by the theorem, to determine $F(X)$ everywhere, if the phases were known. (In principle, the necessary points extend indefinitely in reciprocal space, but by using, say, Gaussian atoms both $d(x)$ and $F(X)$ can be effectively confined to the unit cell and the observable region, respectively.)

For centrosymmetrical structures, to be able to fill in the $|F|^2$ function would suffice to yield the structure, for sign changes could occur only at the points where $|F|^2$ vanishes. The structure corresponding to the $|F|^2$ function is the Patterson of a single unit cell. This has twice the width of the unit cell, and hence to fill in the $|F|^2$ function would require knowledge of $|F|^2$ at the half-integral, as well as the integral h's. This is equivalent to a statement made by Gay (1951).

I think the conclusions which may be stated at this point are:

1. Direct structure determination, for centrosymmetric structures, could be accomplished as well by finding the sizes of the $|F|^2$ at half-integral h as by the usual procedure of finding the signs of the F's at integral h.

2. In work like that of Boyes-Watson, Davidson & Perutz (1947) on haemoglobin, where $|F|^2$ was observed at non-integral h, it would suffice to have only the values at half-integral h.

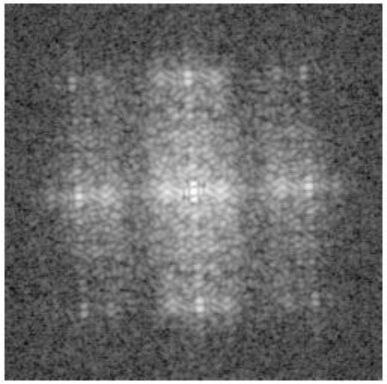
The extension to three dimensions is obvious.

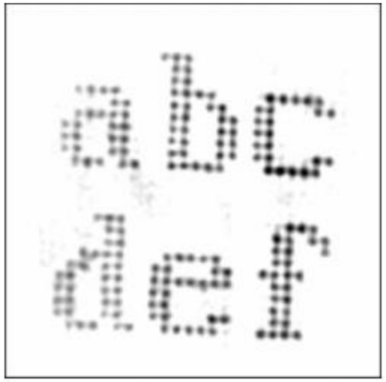
References

Boyes-Watson, J., Davidson, E. & Perutz, M. F. (1947). *Proc. Roy. Soc.* A, **191**, 83.

Gay, R. (1951). Paper presented at the Second International Congress of Crystallography, Stockholm.

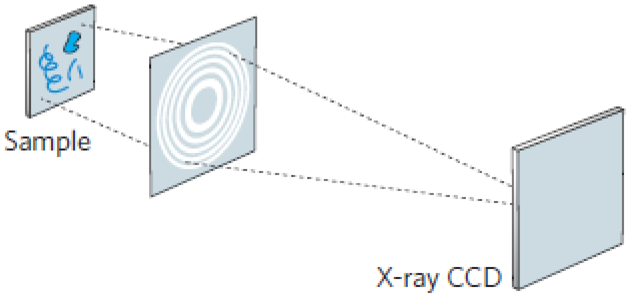
Shannon, C. E. (1949). *Proc. Inst. Radio Engrs., N.Y.* **37**, 10.



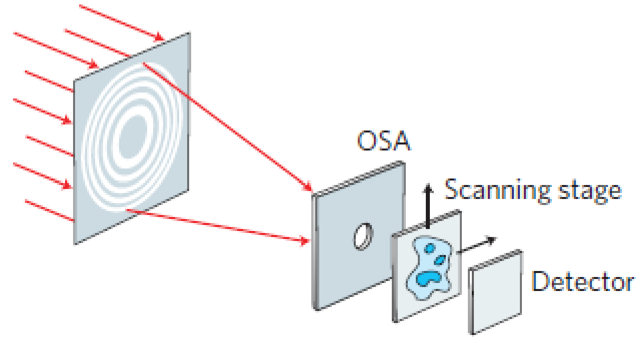


J. Miao, P. Charalambous, J. Kirz, and D. Sayre,
Nature, vol. 400, no. 6742, pp. 342–344, Jul. 1999.

EUV and X-ray Microscopy Techniques



Full-field Zone Plate Microscopy



Scanning Transmission X-ray Microscopy

Sakdinawat and Attwood, *Nature Photonics*, **4**, 840 (2010)

PROSPECTS FOR LONG-WAVELENGTH X-RAY MICROSCOPY AND DIFFRACTION

D. Sayre
IBM Research Center
Yorktown Heights, New York 10598, U.S.A.

in merely by laying down the function $\sin \pi a X / \pi a X$ at each of the above points, with weight equal to the value of $F(X)$ at that point, and adding.

Now the electron-density function $d(x)$ describing a single unit cell of a crystal vanishes outside the points $x = \pm a/2$, where a is the length of the cell. The reciprocal-lattice points are at $X = 0, \pm 1/a, \pm 2/a, \ldots$, and hence the experimentally observable values of $F(X)$ would suffice, by the theorem, to determine $F(X)$ everywhere, if the phases were known. (In principle, the necessary points extend indefinitely in reciprocal space, but by using, say, Gaussian atoms both $d(x)$ and $F(X)$ can be effectively confined to the unit cell and the observable region, respectively.)

For centrosymmetrical structures, to be able to fill in the $|F|^2$ function would suffice to yield the structure, for sign changes could occur only at the points where $|F|^2$ vanishes. The structure corresponding to the $|F|^2$ function is the Patterson of a single unit cell. This has

1. Direct structure determination, for centrosymmetric structures, could be accomplished as well by finding the sizes of the $|F|^2$ at half-integral h as by the usual procedure of finding the signs of the F's at integral h.

2. In work like that of Boyes-Watson, Davidson & Perutz (1947) on haemoglobin, where $|F|^2$ was observed at non-integral h, it would suffice to have only the values at half-integral h.

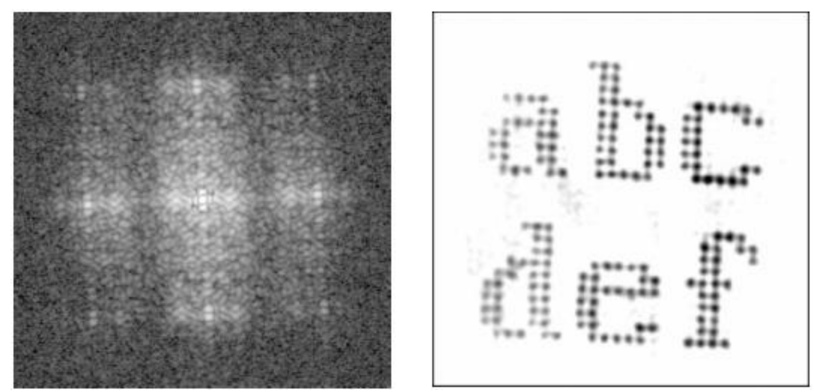
The extension to three dimensions is obvious.

References

Boyes-Watson, J., Davidson, E. & Perutz, M. F. (1947). *Proc. Roy. Soc.* A, **191**, 83.

Gay, R. (1951). Paper presented at the Second International Congress of Crystallography, Stockholm.

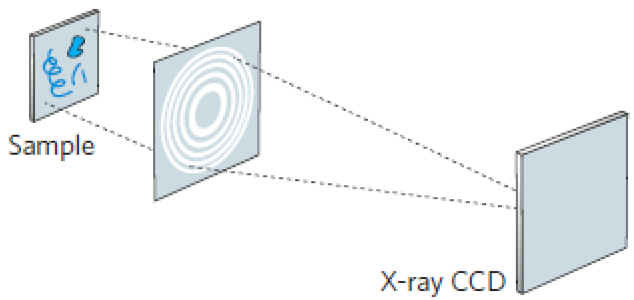
Shannon, C. E. (1949). *Proc. Inst. Radio Engrs., N.Y.* **37**, 10.



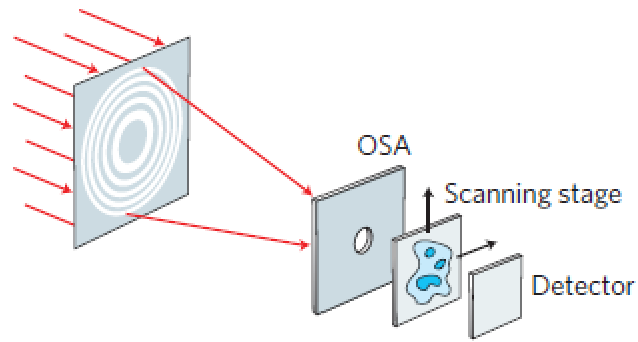
J. Miao, P. Charalambous, J. Kirz, and D. Sayre,
Nature, vol. 400, no. 6742, pp. 342–344, Jul. 1999.

D. Sayre, in Lecture Notes in Physics,
Vol. 112, Imaging Processes and Coherence in Physics,
1980, pp. 229–235.

EUV and X-ray Microscopy Techniques



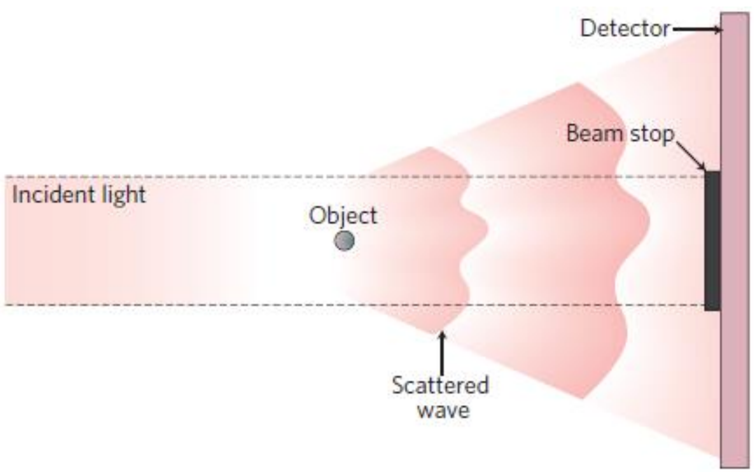
Full-field Zone Plate Microscopy



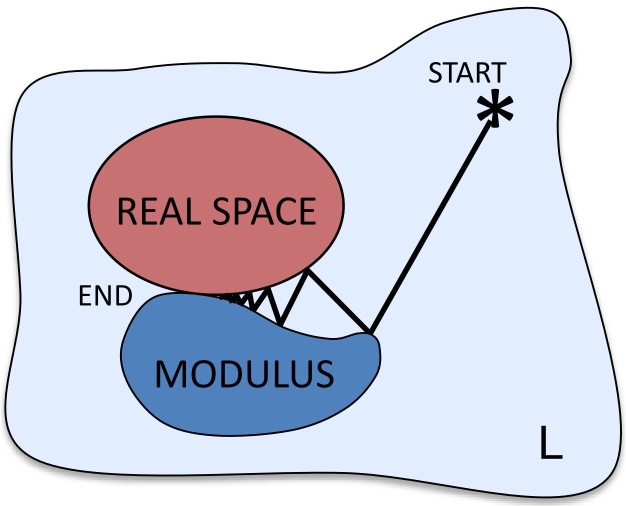
Scanning Transmission X-ray Microscopy

Sakdinawat and Attwood, *Nature Photonics*, **4**, 840 (2010)

Coherent Diffractive Imaging (CDI)



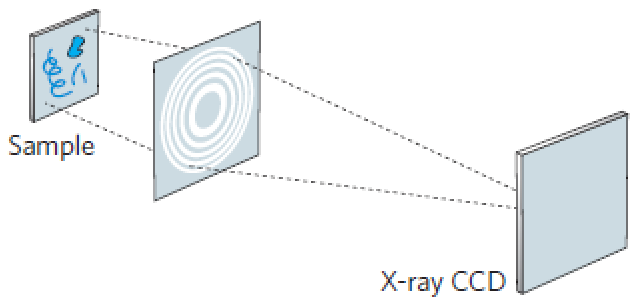
2D Phase Retrieval



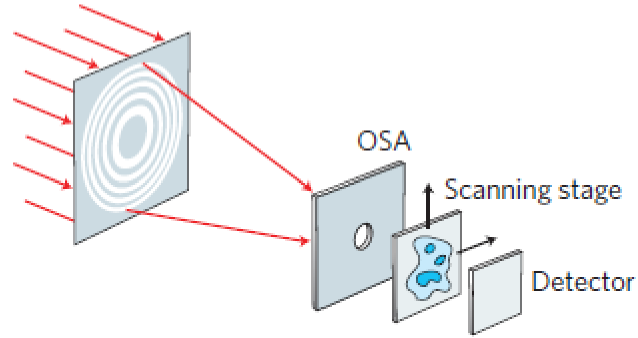
Miao et al., *Nature* **400**, 342 (1999)
Chapman and Nugent, *Nature Photonics*, **4**, 833 (2010)

J. R. Fienup, *Opt. Lett.*, vol. 3, no. 1, pp. 27–29, Jul. 1978.

EUV and X-ray Microscopy Techniques



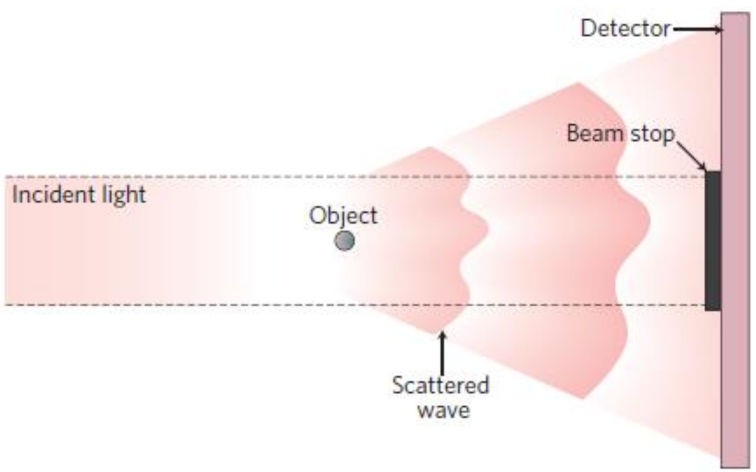
Full-field Zone Plate Microscopy

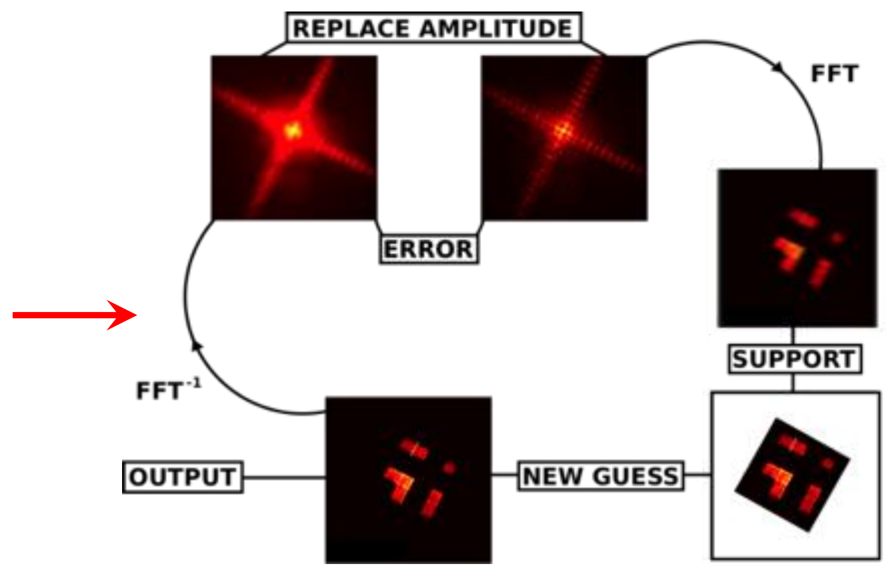


Scanning Transmission X-ray Microscopy

Sakdinawat and Attwood, *Nature Photonics*, **4**, 840 (2010)

Coherent Diffractive Imaging (CDI)



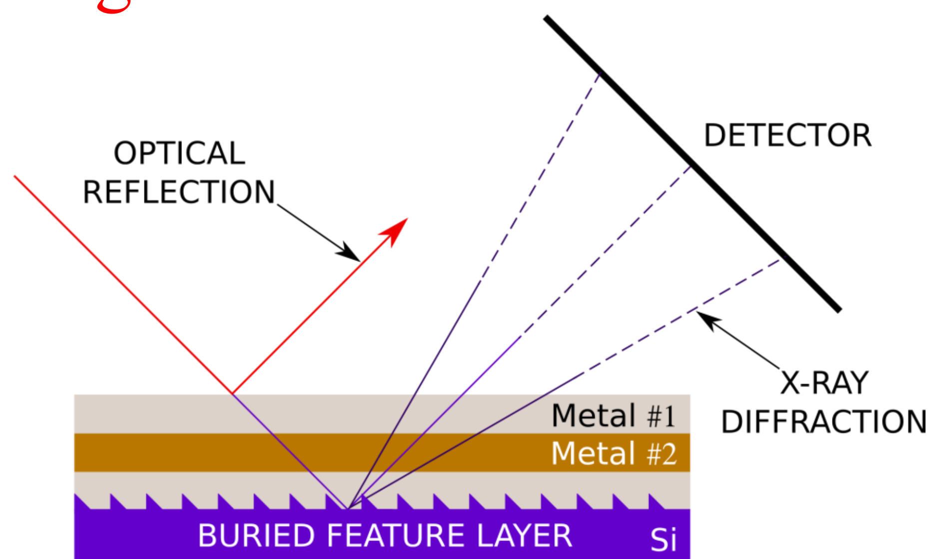


Miao et al., *Nature* **400**, 342 (1999)
Chapman and Nugent, *Nature Photonics*, **4**, 833 (2010)

J. R. Fienup, *Opt. Lett.*, vol. 3, no. 1, pp. 27–29, Jul. 1978.

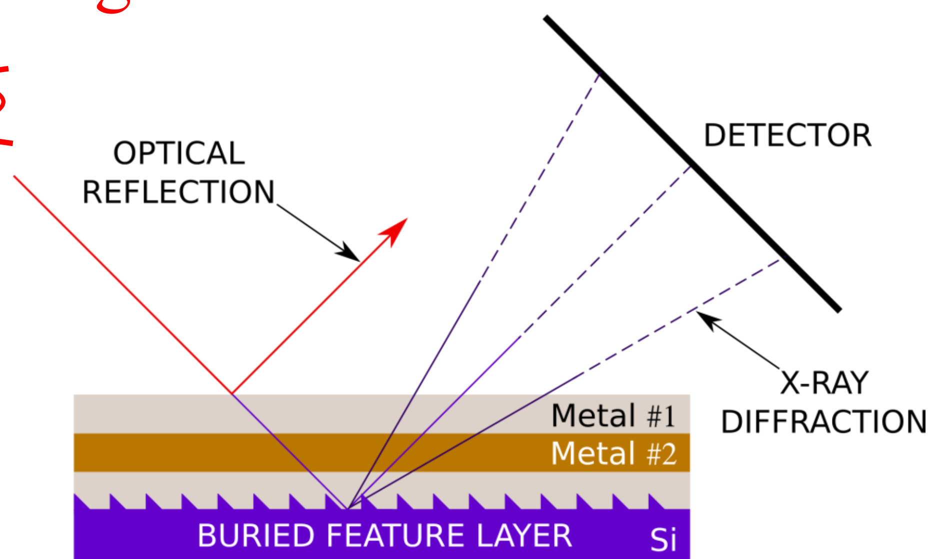
EUV and X-ray Microscopy

- No Aberrations – **Diffraction-limited**
- Image Through Thick Samples
- Image Buried Samples
- Inherent Elemental Contrast Of X-rays
- Necessarily a Phase Contrast Technique
- Requires A Coherent Beam Of Light
- Requires An Isolated Sample



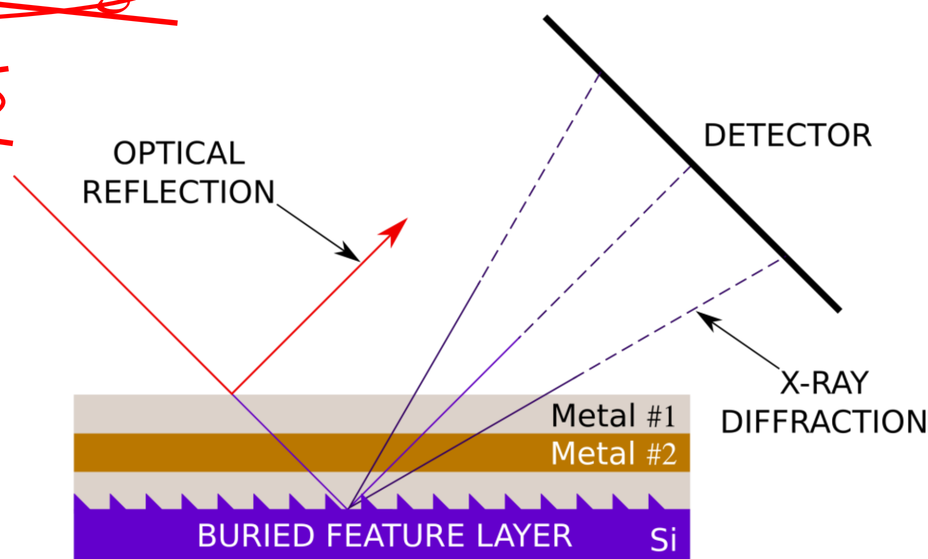
EUV and X-ray Microscopy

- No Aberrations – **Diffraction-limited**
- Image Through Thick Samples
- Image Buried Samples
- Inherent Elemental Contrast Of X-rays
- Necessarily a Phase Contrast Technique
- Requires A Coherent Beam Of Light
- Requires An ~~Isolated Sample~~

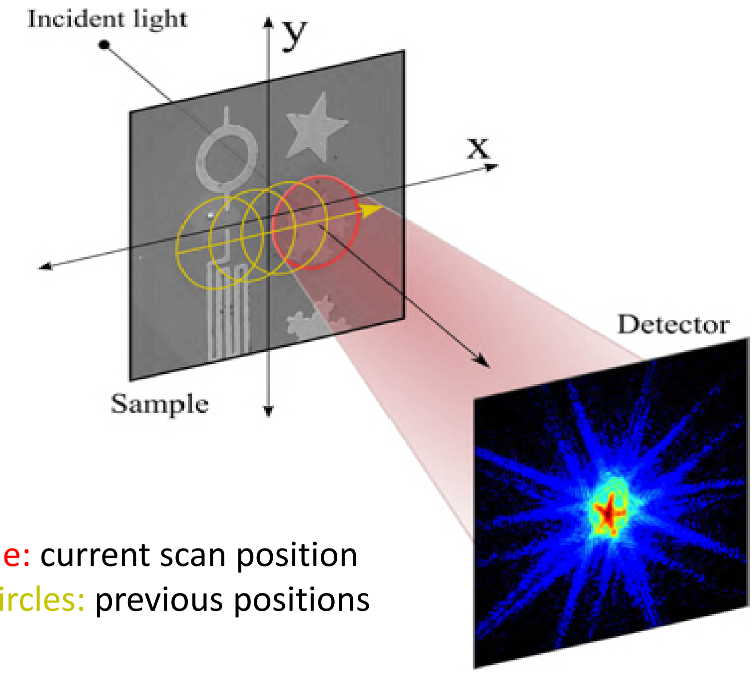


EUV and X-ray Microscopy

- No Aberrations – **Diffraction-limited**
- Image Through Thick Samples
- Image Buried Samples
- Inherent Elemental Contrast Of X-rays
- Necessarily a Phase Contrast Technique
- Requires A ~~Coherent Beam Of Light~~
- Requires An ~~Isolated Sample~~

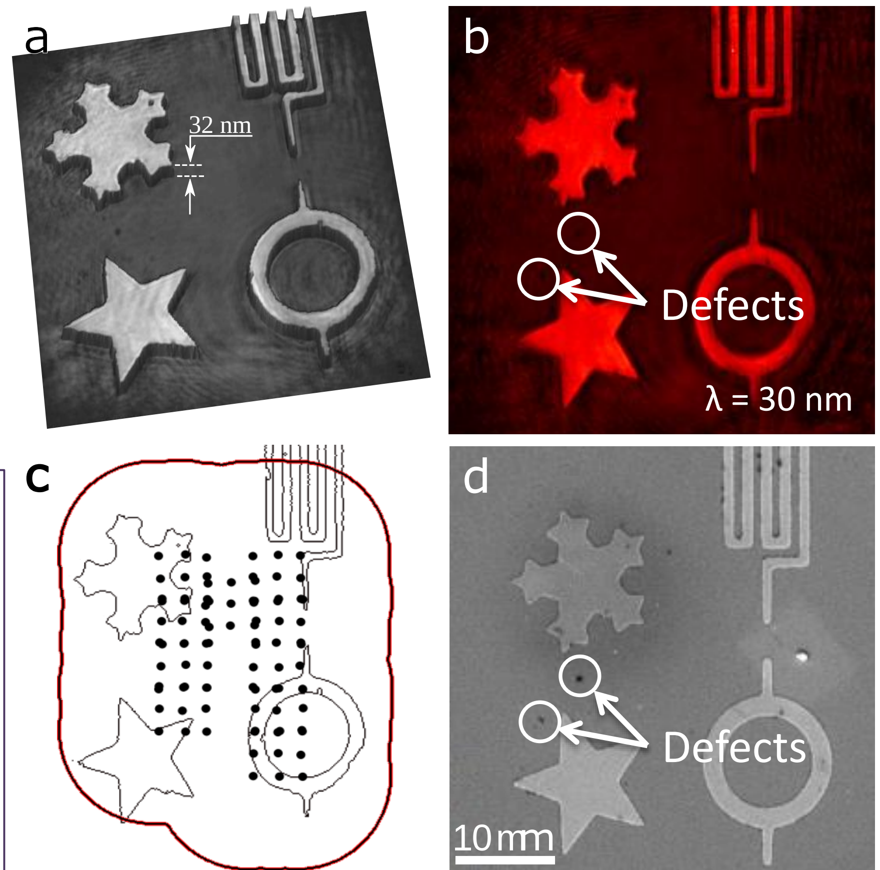


Ptychography CDI



Red circle: current scan position
Yellow circles: previous positions

Phase Contrast Microscopy Through Phase Retrieval



Seaberg et. al, Optica 1, 1 39-44

Beam scatters at many overlapping positions

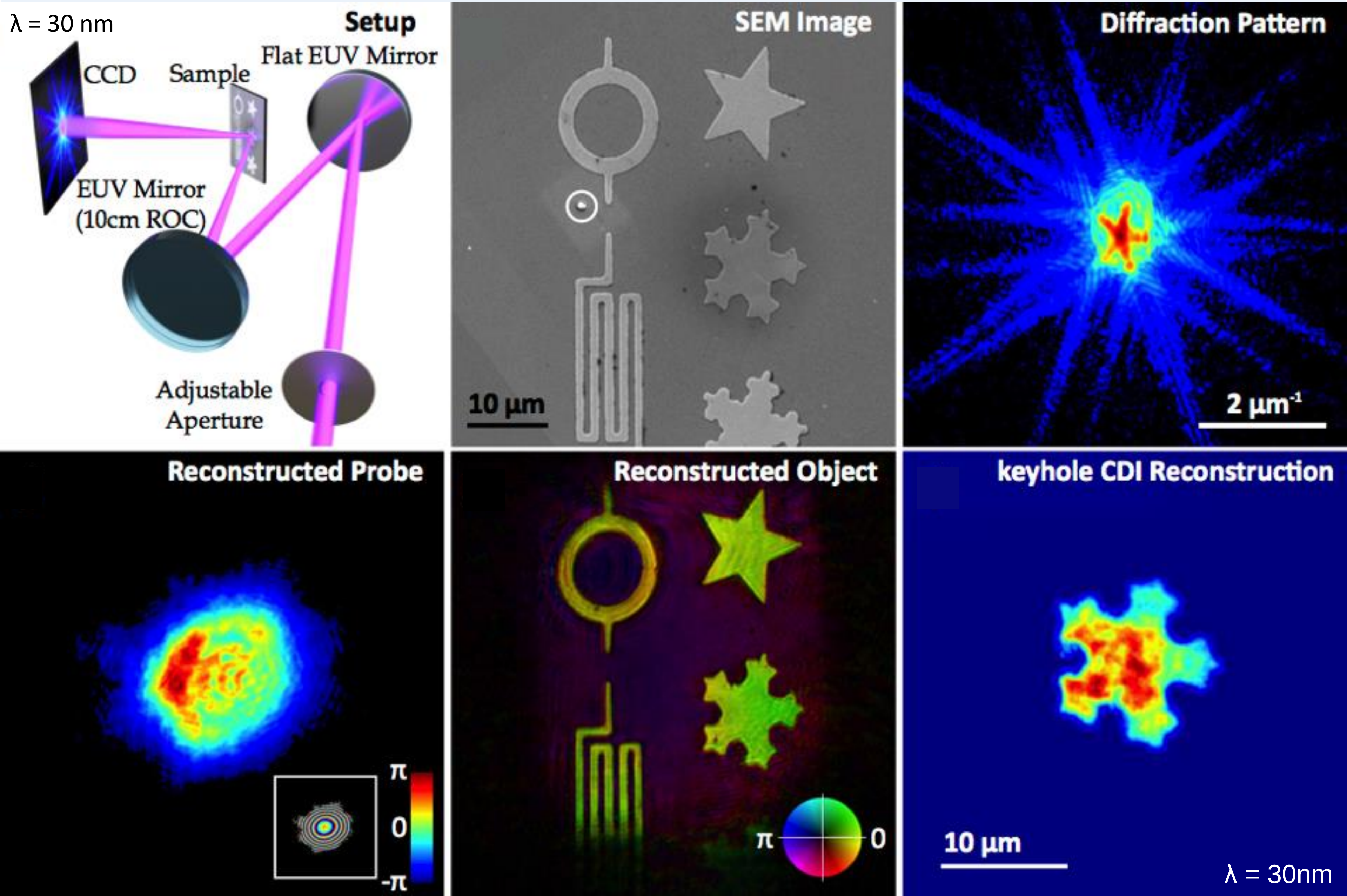
Constraints:

1) Measured data (many positions)
2) Oversampled illumination
3) Overlap between positions

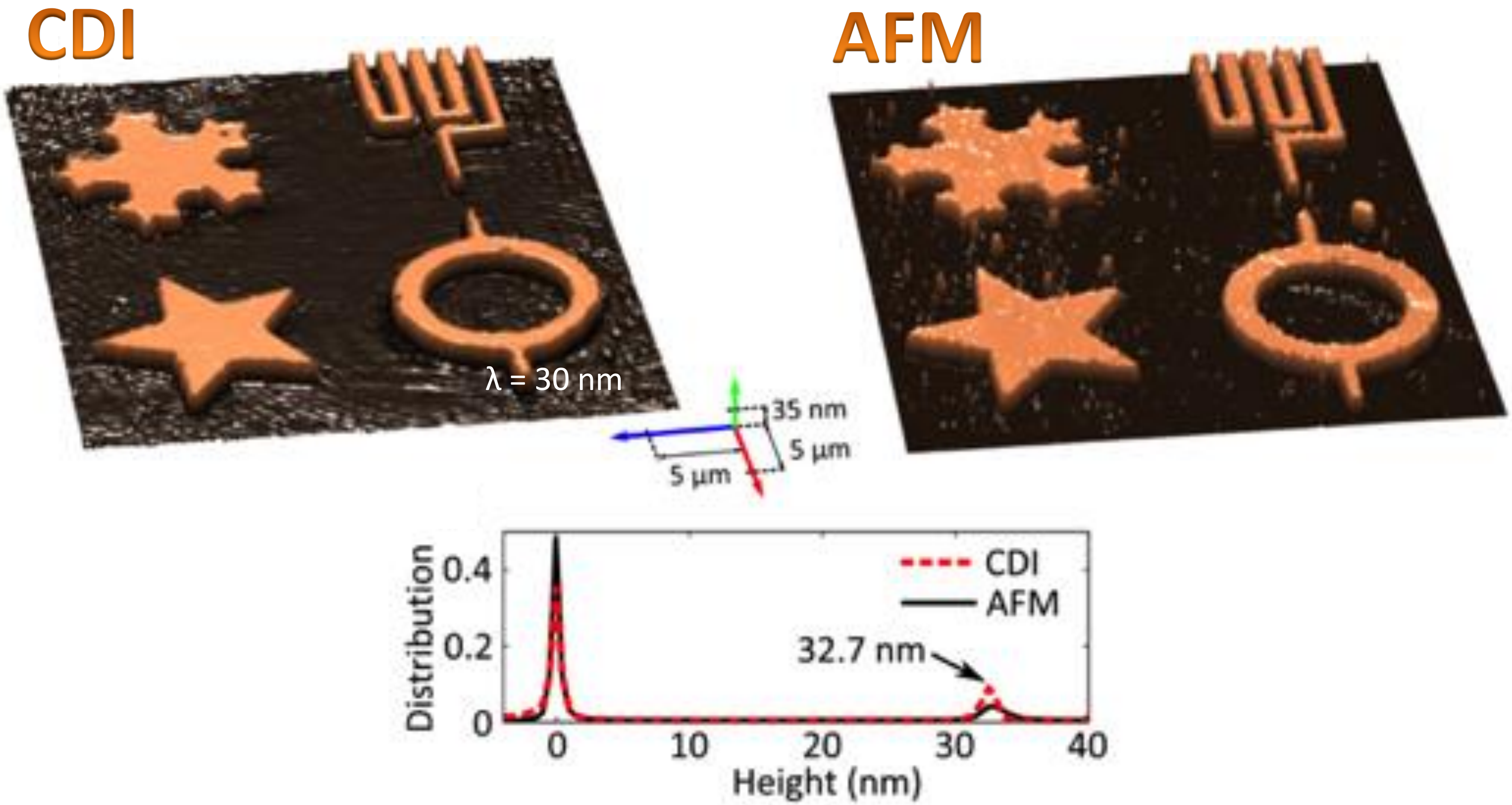
Curved wave-front forms shadowgram
Simultaneously retrieves beam and object

Thibault *et al.*, *Science* **321,** 379 (2008)
Maiden *et al.*, *Ultramicroscopy* **109,** 1256 (2009)

High Fidelity Reflection CDI with an HHG Source



Quantitative Topology Through Reflection CDI

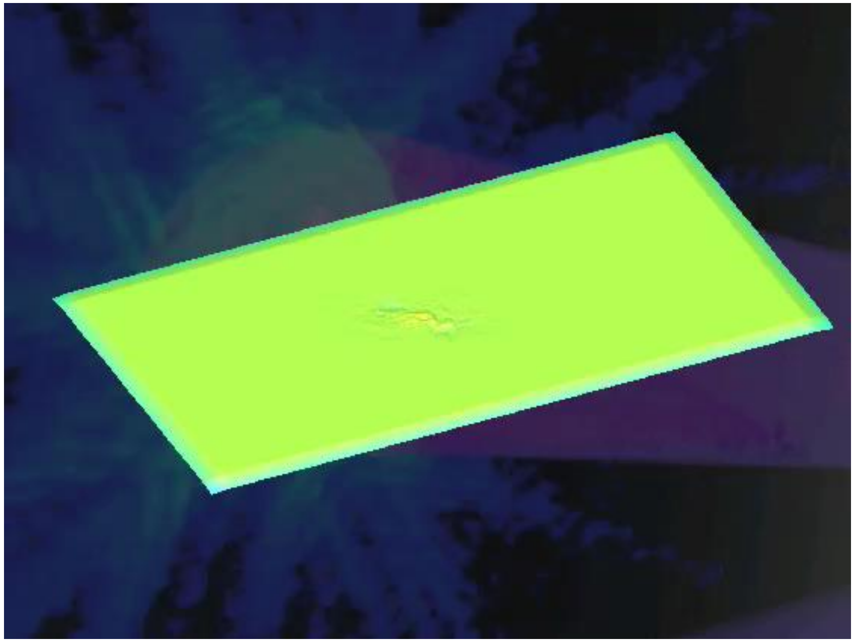


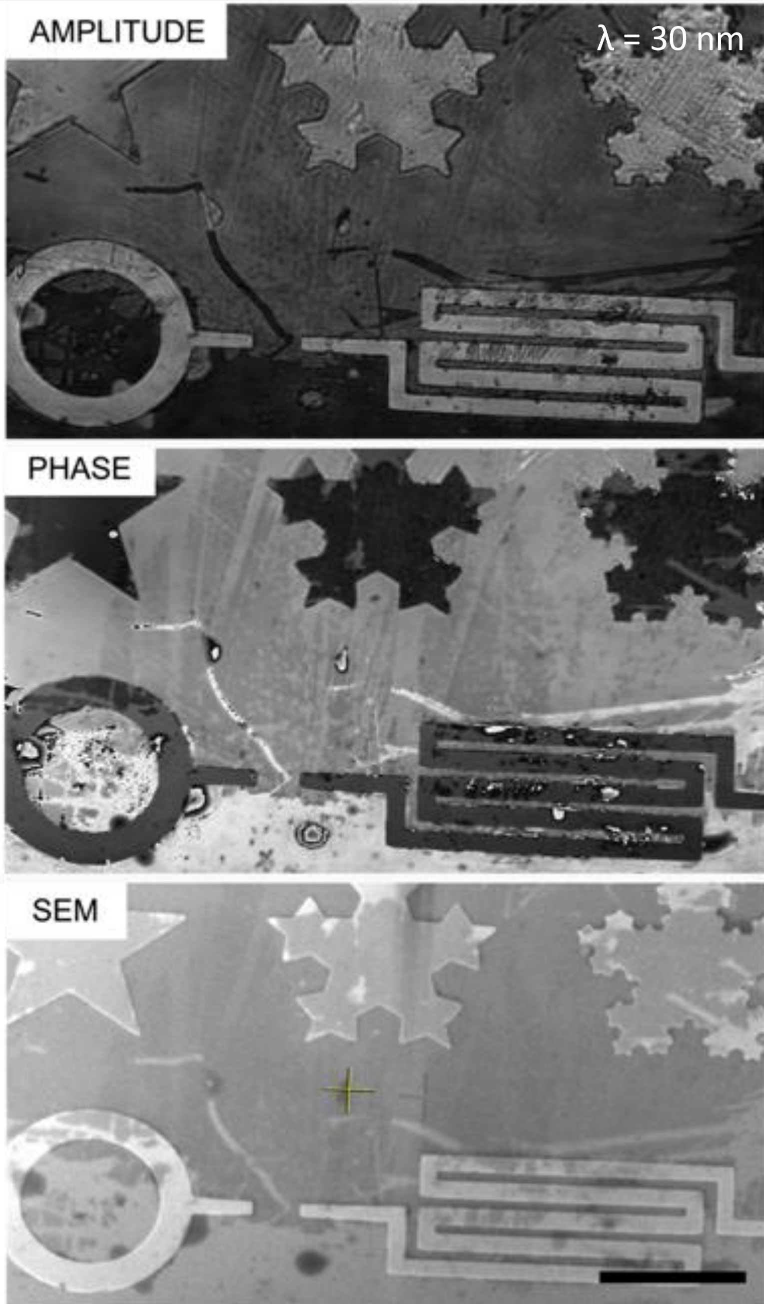
Seaberg et. al, Optica 1, 1 39-44

- Must Take Fresnel Reflections into Account (including oxide layers)
- Ellipsometry to Find oxide thickness (otherwise relative profilometry)
- CDI and AFM agree ±3Å

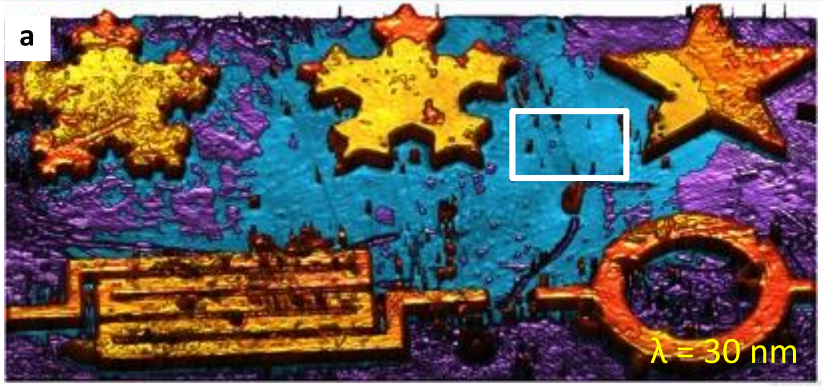
High Fidelity Reflection CDI with an HHG Source

- **200 Positions**
- **0.1 seconds/position**
- **1 min total exposure**
- **Can be cut to 30 seconds!**
- **45nm transverse resolution**
- **0.5 nm axial precision**
- **High Contrast v. SEM**
- **ALGORITHMS CORRECT ERRORS**





Quantitative Topology Through Reflection CDI

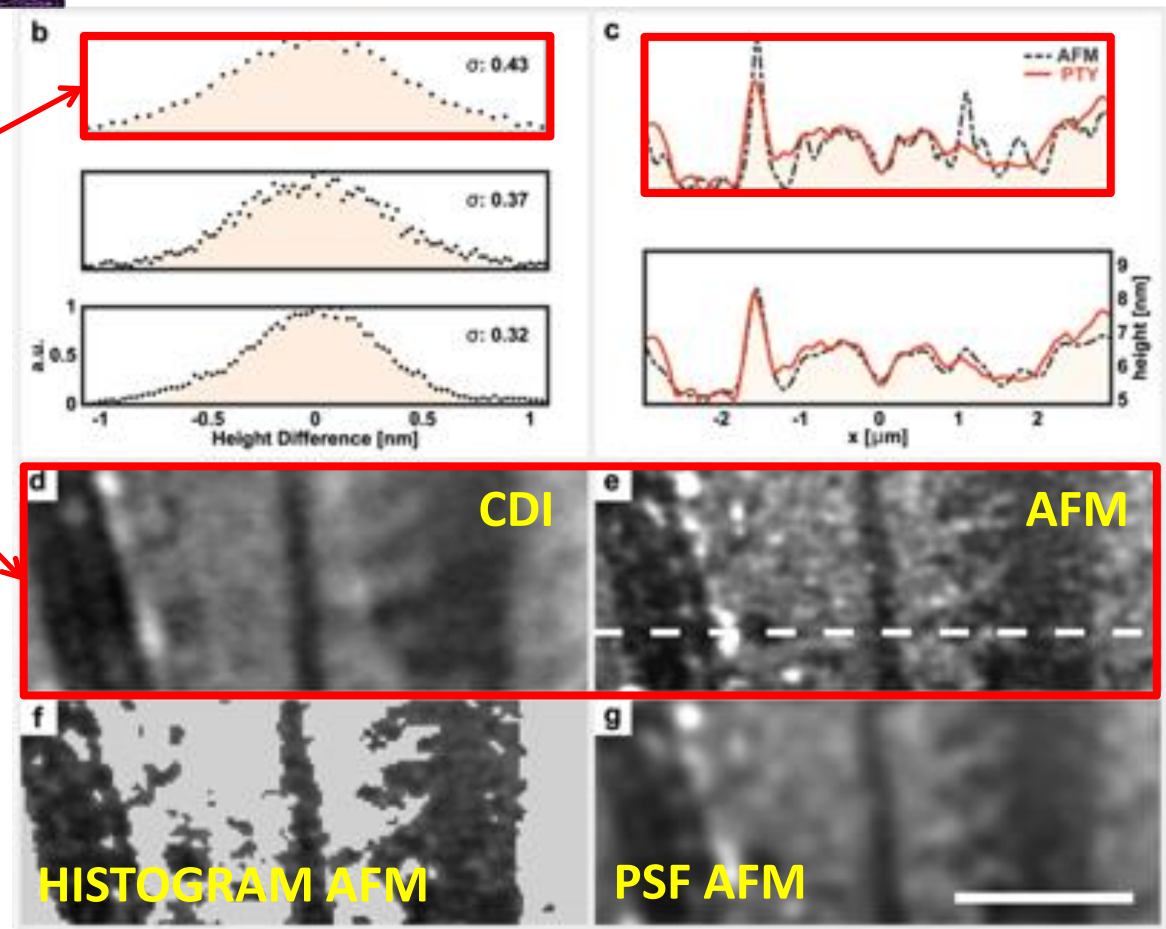


Zhang et. al, Submitted

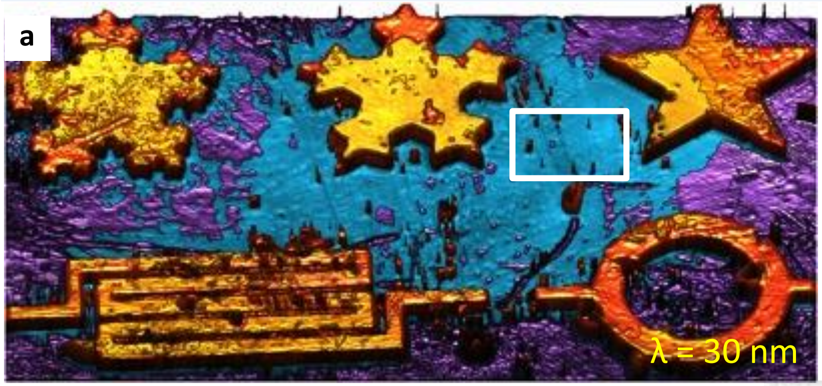
- Small debris is weakly scattering
- Out-shined by titanium shapes
- Filter so transverse resolutions match

NO FILTERING

σ = 4.3 Å



Quantitative Topology Through Reflection CDI

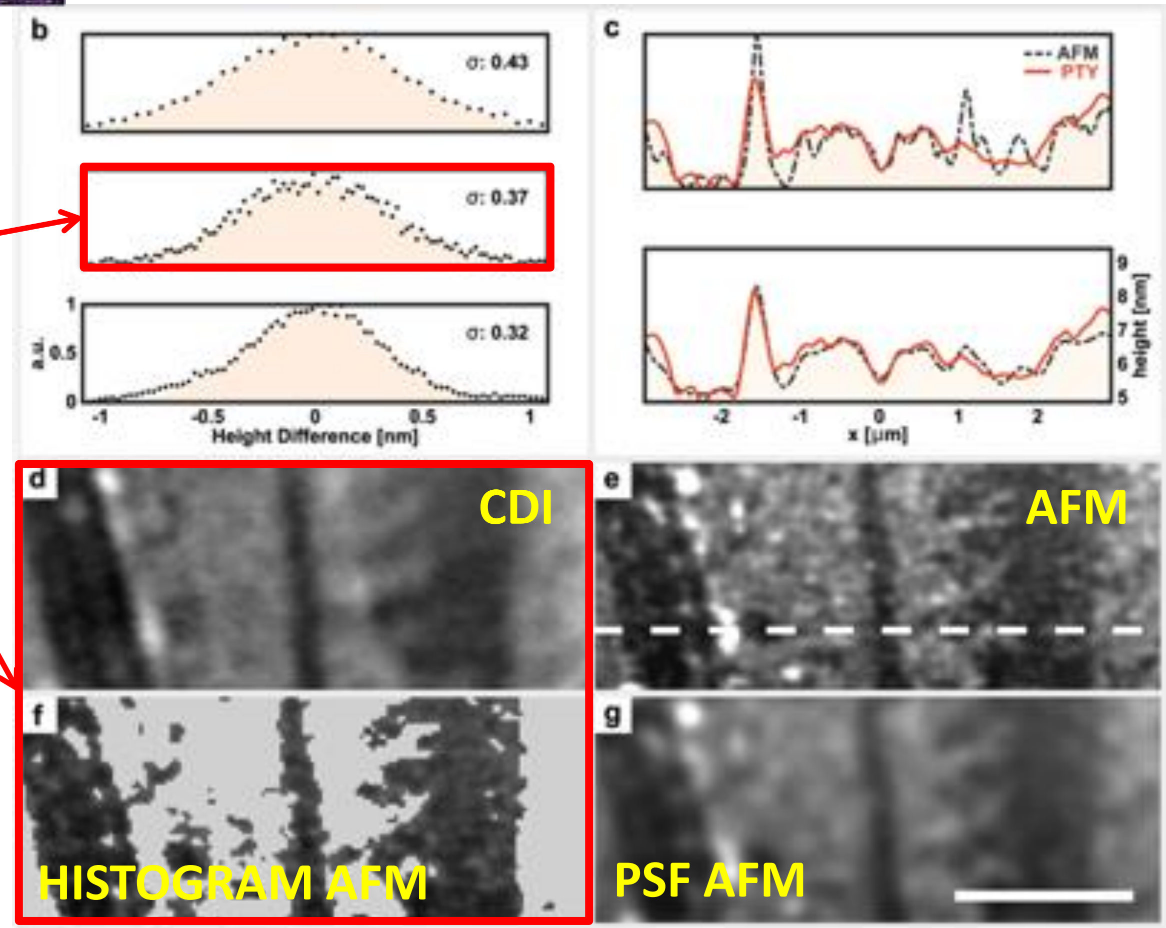


Zhang et. al, Submitted

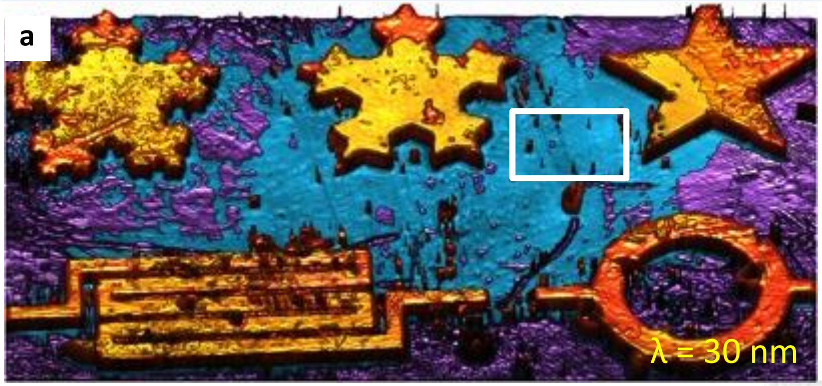
- Small debris is weakly scattering
- Out-shined by titanium shapes
- Filter so transverse resolutions match

HISTOGRAM FILTER

σ = 3.7 Å



Quantitative Topology Through Reflection CDI

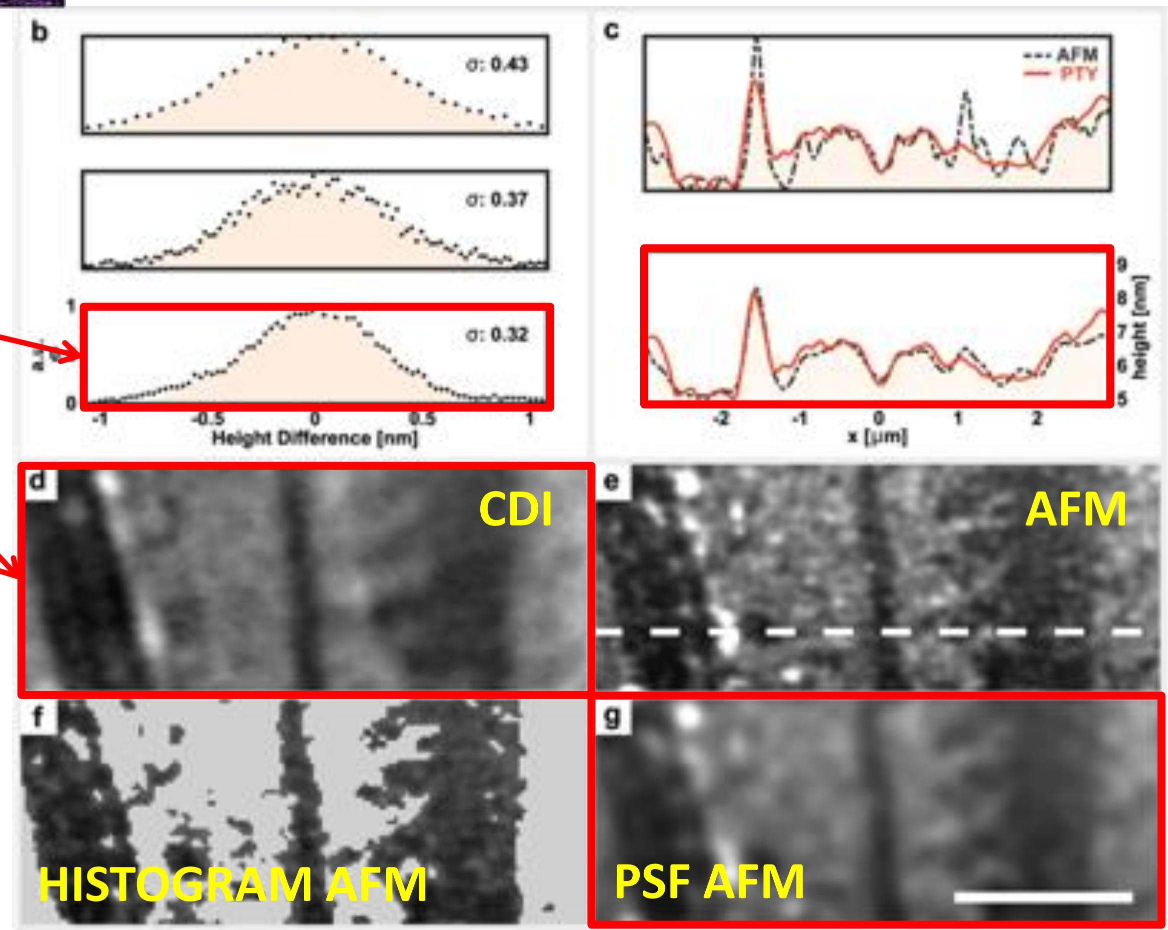


Zhang et. al, Submitted

- Small debris is weakly scattering
- Out-shined by titanium shapes
- Filter so transverse resolutions match

PSF FILTERING

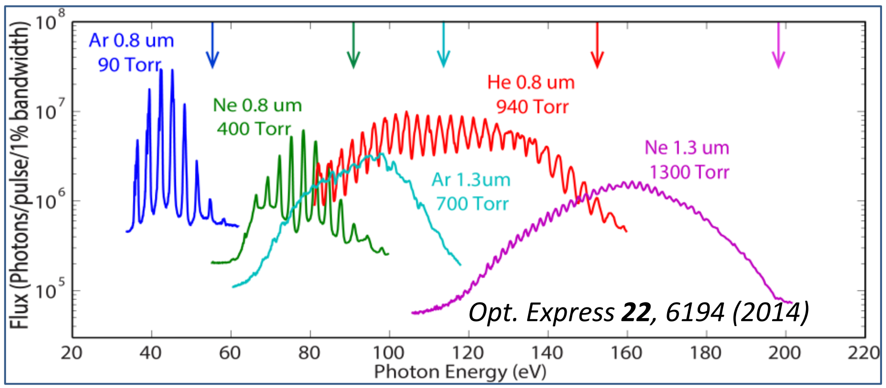
σ = 3.2 Å

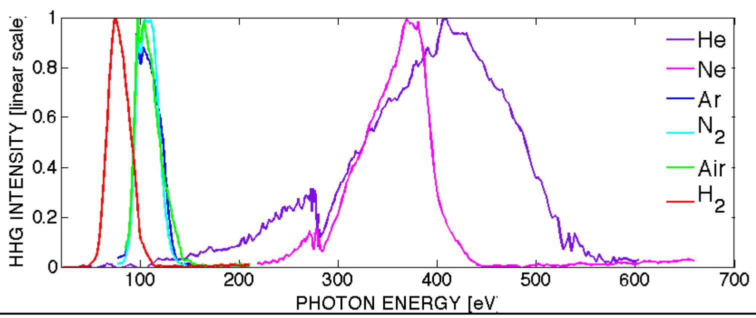


Precise Control ⟶ High Precision Measurement

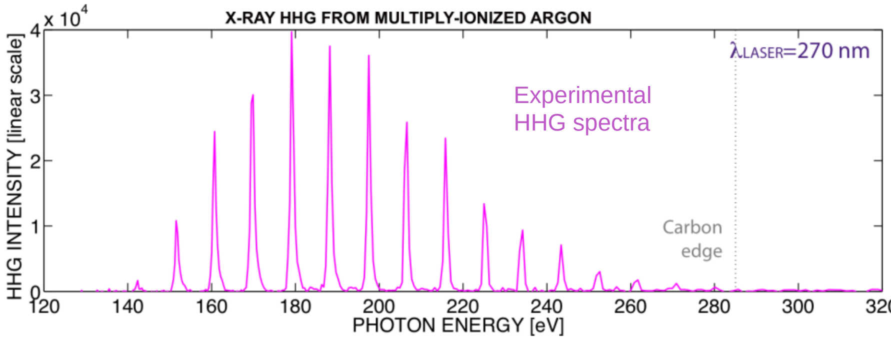
- MID-IR LASERS ➔ X-RAY CONTINUUM ➔ SPECTROSCOPY
- UV LASERS ➔ ISOLATED HHG PEAKS ➔ IMAGING/METROLOGY
- CIRCULAR POLARIZATION ➔ ISOLATED HHG PEAKS ➔ IMAGING/METROLOGY

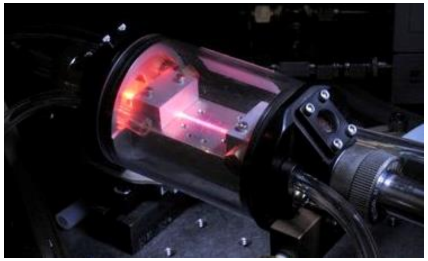
Mid-infrared driven soft x-ray HHG





UV driven soft x-ray HHG



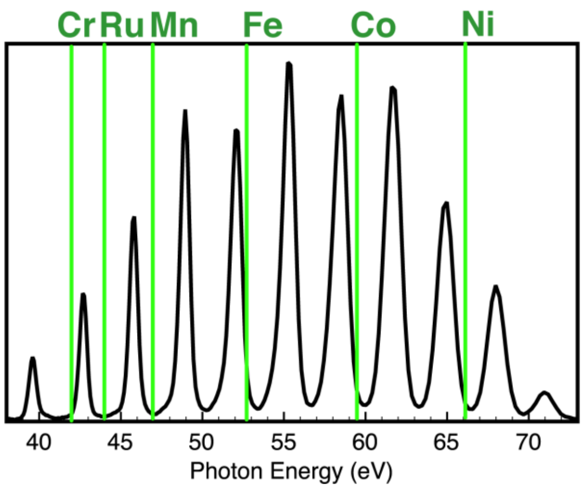


US Patent Awarded, US 61873794 (2015)
Postdeadline paper, CLEO (2014)

Precise Control ⟶ High Precision Measurement

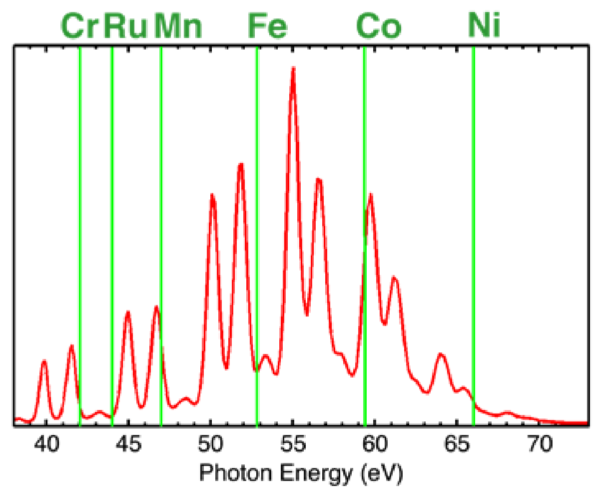
Linearly polarized EUV HHG

- Odd harmonics of fundamental



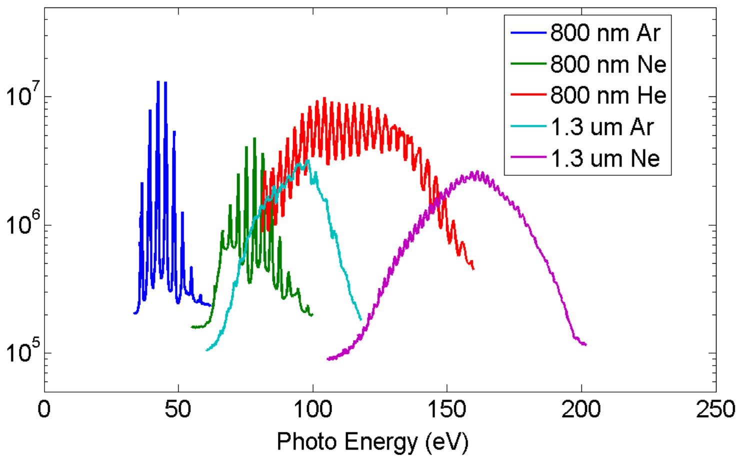
Circularly polarized EUV HHG

- Right and left circular, every 3rd missing



Linearly polarized soft X-ray HHG

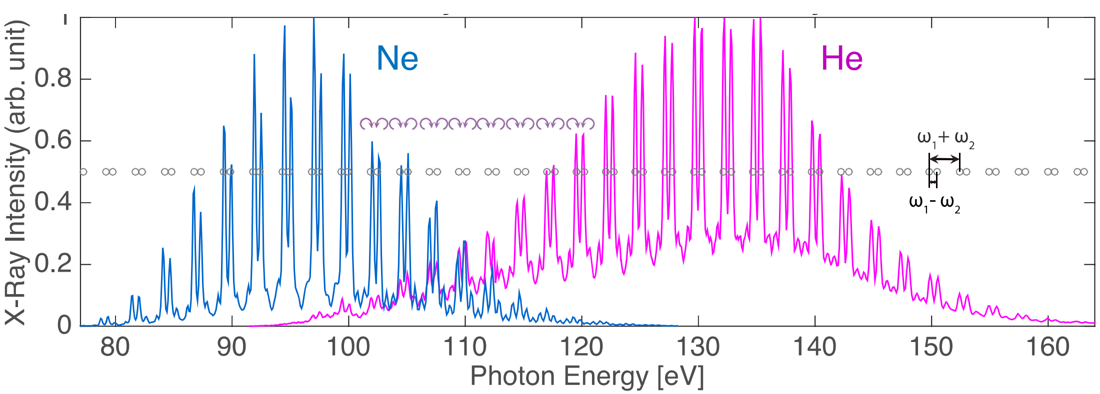
- Broad super-continuum



Science ***336***, *1287 (2012); Op. Ex.* ***22***, *6194 (2014)*

Circularly polarized EUV HHG

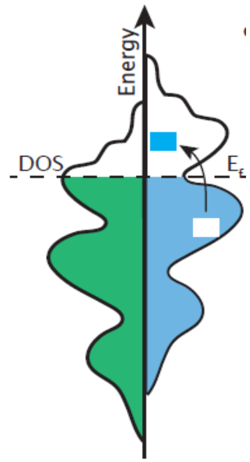
- Right and left circular, narrow peaks



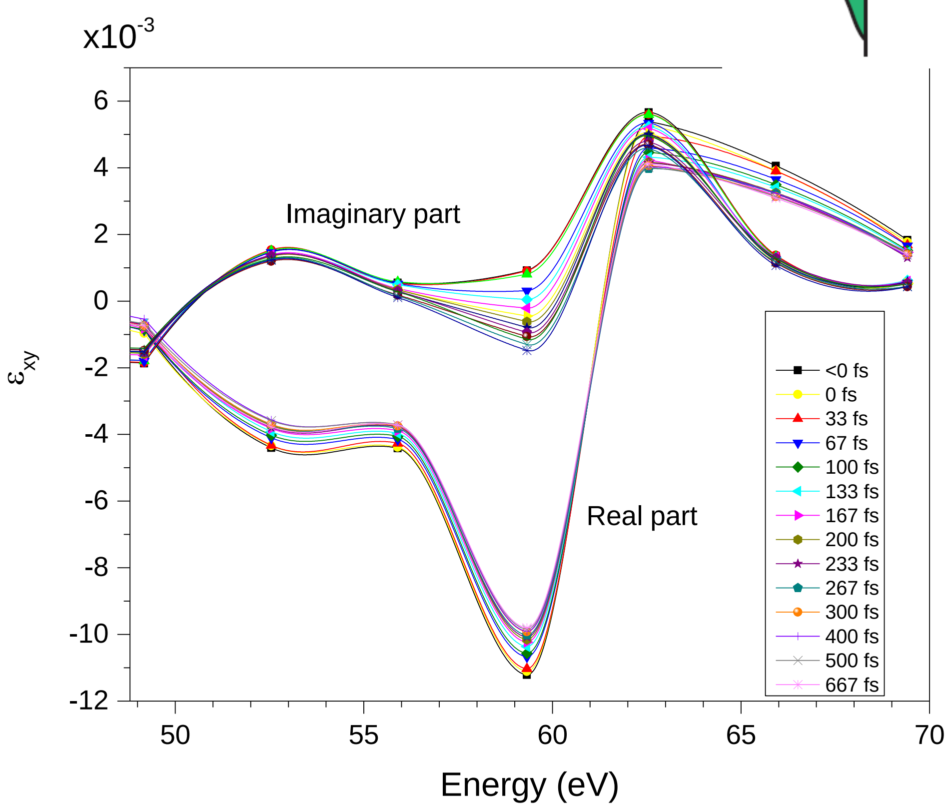
Postdeadline paper JTh5C.1, CLEO (2015)

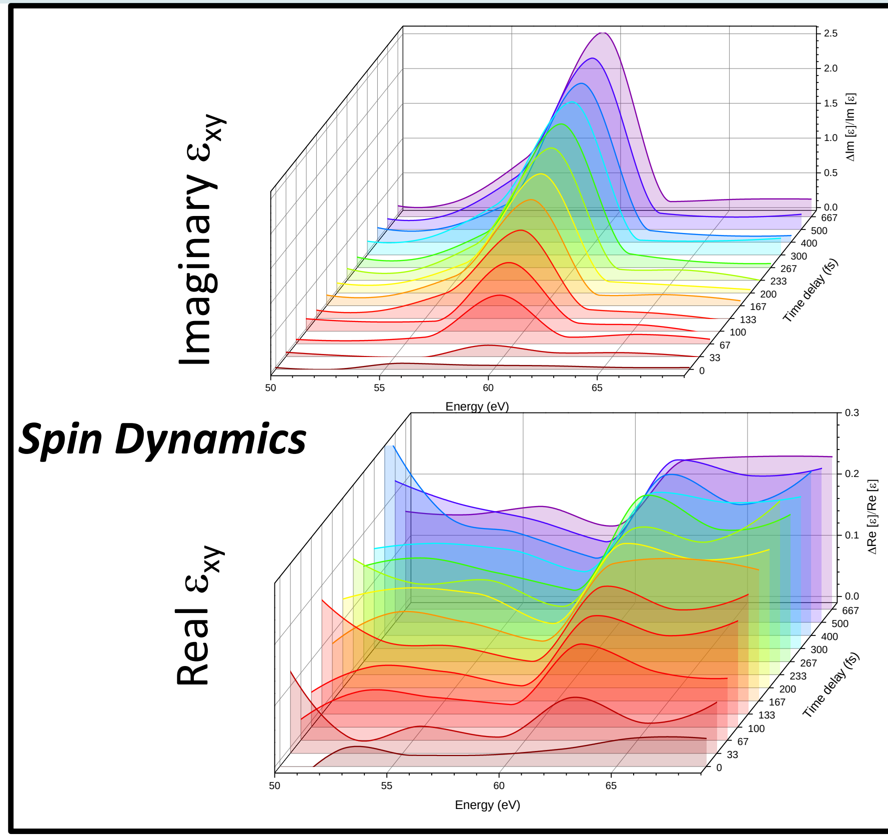
Example: Time Resolved EUV Ellipsometry

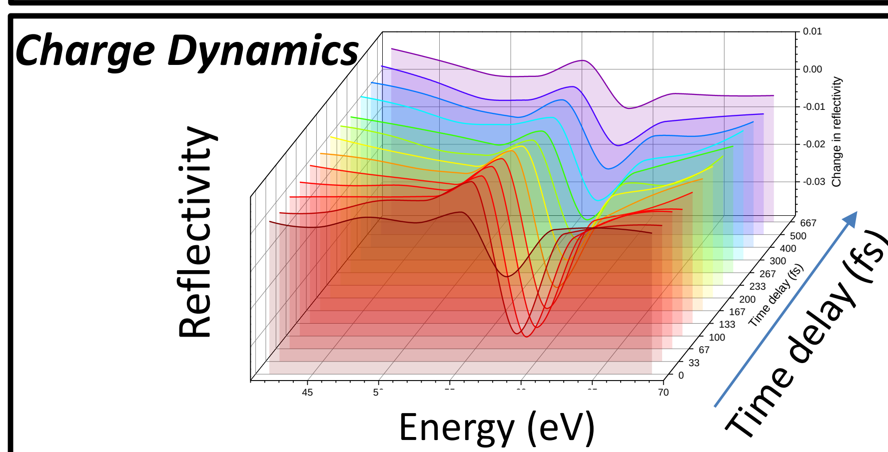
- Extract time-dependent magneto-optic constant: $\varepsilon_{xy}(t)$ and $\varepsilon_{xx}(t)$



$$\varepsilon_{xy}(\omega,t)$$

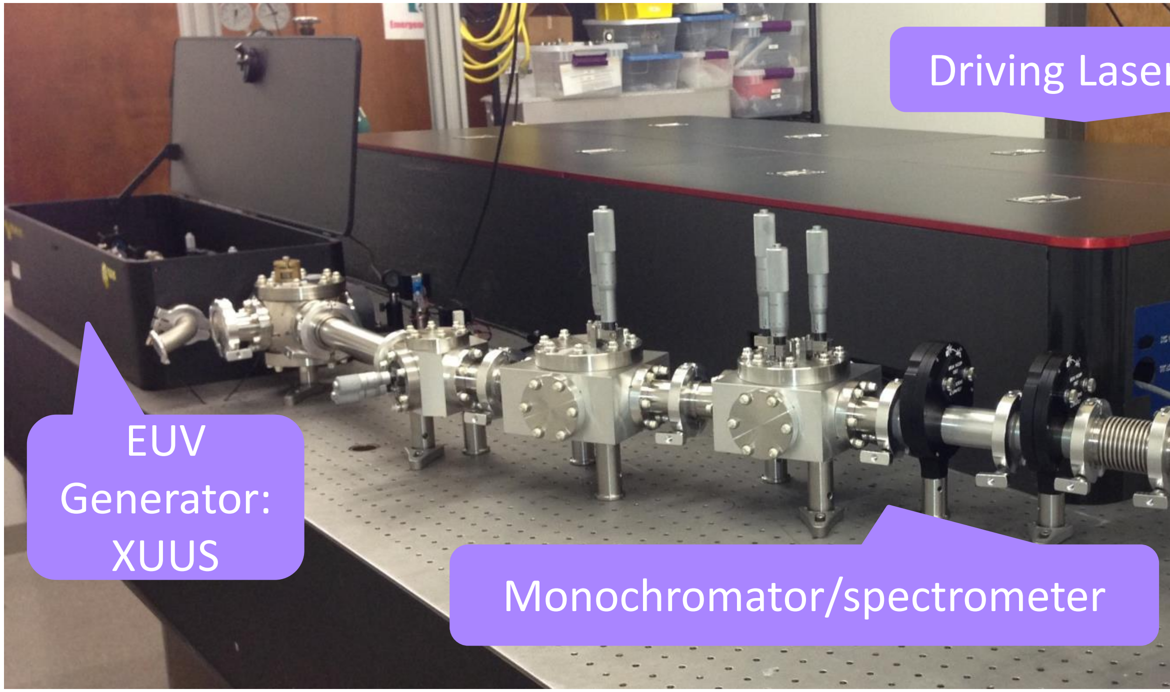






Turgut et al., in prep (2015)

Commercial HHG Source and Beam-line



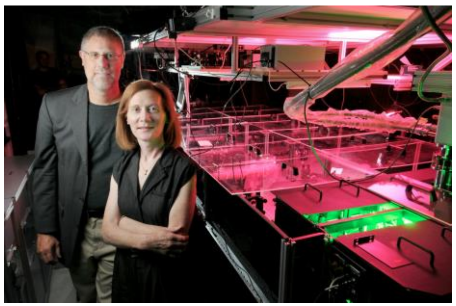
- Interest from biomedical industry allowing KMLabs to engineer laser – **Y-Fi**
- Phase IIb DOE SBIR grant allowing us to **engineer** commercial EUV source with ultrastable automatic laser alignment - **XUUS 4**

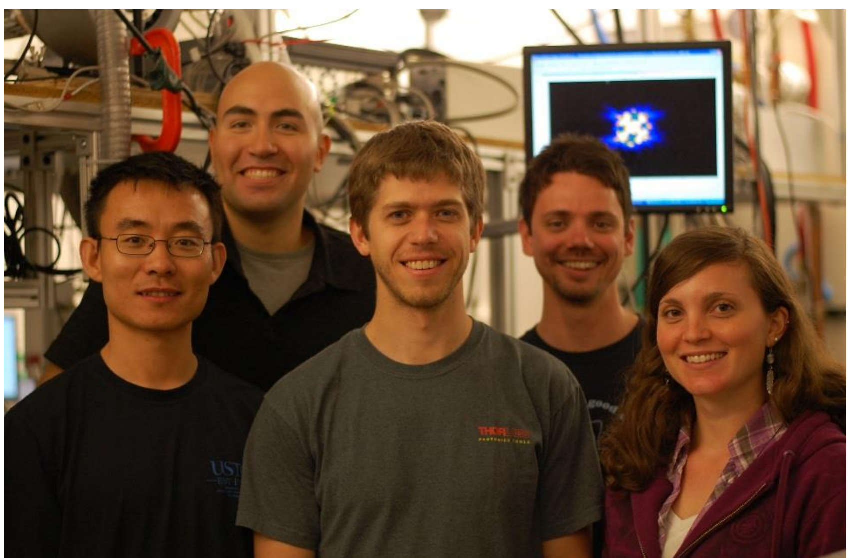
XUUS at CLEO

XUUS4
generation coherent
EUV source
EUV output >10¹² ph/sec
Stable, efficient HHG waveguide
Active, 4-axis pointing stabilization
Growing family of beamline modules
Industry Leading
High Harmonic
Generation
20 KMLABS
LEADING IN ULTRAFAST
1994-2014
femtosecond
EUV
X-Ray
XUUS
RED DRAGON
WYVERN HE
WYVERN
KMLABS
XUUS4
SMART

Acknowledgements

- **Funding Agencies:** DARPA, SRC, NSF, AFOSR
- **Support**: Margaret Murnane, Henry Kapteyn, Sterling Backus, Chris Wood…





- **Students:** Matthew Seaberg, Bosheng Zhang, Dennis Gardner, Elisabeth Shanblatt, Christina Porter, Robert Karl, Michael Tanksalvla, Charlie Bevis
- **Collaborators**: Jianwei Miao, Eric Gullikson, Carmen Menoni, Bill Schlotter, Erik Anderson, Brian Abbey…